

DEVELOPMENT OF THERMAL BARRIERS FOR SOLID ROCKET MOTOR NOZZLE JOINTS

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Solid Rocket Motor Nozzle Joints

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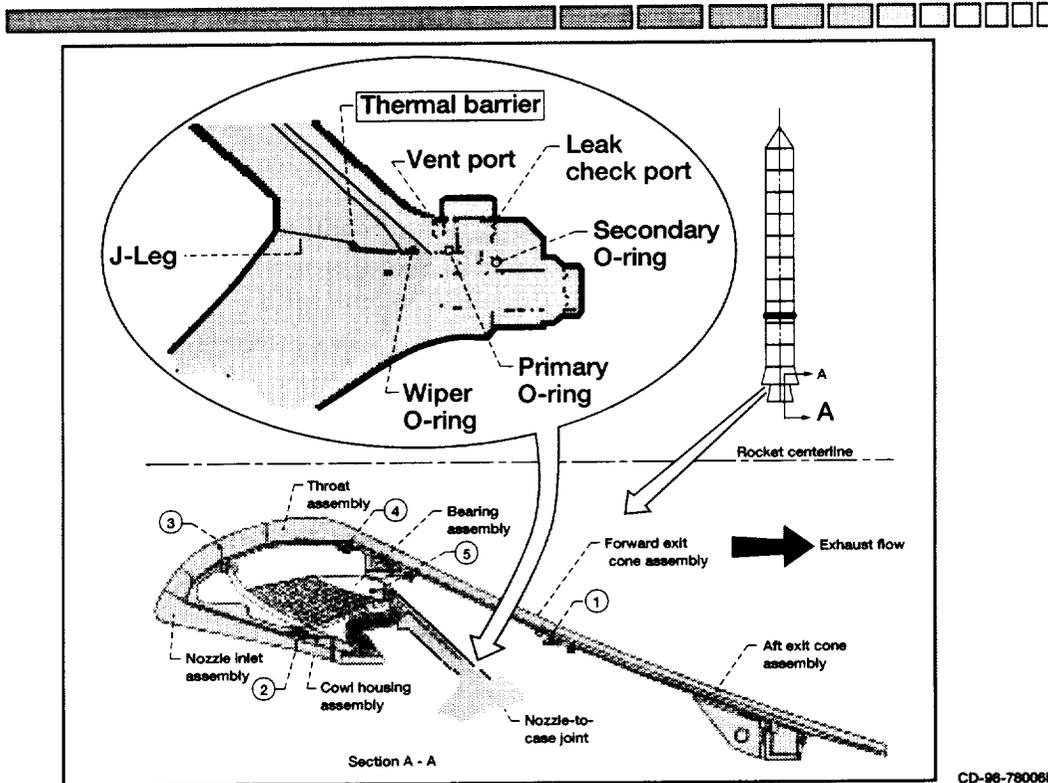
Background

- Shuttle RSRM Joints are sealed with O-rings to contain rocket pressure (to 900 psi) and prevent outflow of high temperature (5500 °F) combustion gases. Motors are insulated with either phenolic or rubber insulation. Joint gaps are generally filled with joint-fill compounds.
- Current RSRM nozzle-to-case joint design incorporating primary, secondary, and wiper O-rings, expected to experience gas paths through the joint-fill compound (polysulfide) to the inner-most wiper O-ring in about 1 out of 7 motors.
- Hot gas flow to the wiper O-ring is an undesirable condition that Thiokol/NASA wants to eliminate. Though it poses no safety hazard to the motor, each nozzle-to-case joint gas path results in extensive reviews and evaluation requiring close-out prior to resuming flight.
- Thiokol/NASA Marshall are currently working to improve the nozzle-to-case joint design by implementing the more reliable J-Leg design (used successfully in field and igniter joints), NASA Glenn thermal barrier, and eliminate the joint-fill compound.

CD-98-77995a

Joints in the Space Shuttle solid rocket motors are sealed by O-rings to contain combustion gases inside the rocket that reach pressures of up to 900 psi and temperatures of up to 5500°F. To provide protection for the O-rings, the motors are insulated with either phenolic or rubber insulation. Gaps in the joints leading up to the O-rings are filled with polysulfide joint-fill compounds as an additional level of protection. The current RSRM nozzle-to-case joint design incorporating primary, secondary, and wiper O-rings experiences gas paths through the joint-fill compound to the innermost wiper O-ring in about one out of every seven motors. Although this does not pose a safety hazard to the motor, it is an undesirable condition that NASA and rocket manufacturer Thiokol want to eliminate. Each nozzle-to-case joint gas path results in extensive reviews and evaluation before flights can be resumed. Thiokol and NASA Marshall are currently working to improve the nozzle-to-case joint design by implementing a more reliable J-leg design that has been used successfully in the field and igniter joints. They are also planning to incorporate the NASA Glenn braided carbon fiber thermal barrier into the joint. The thermal barrier would act as an additional level of protection for the O-rings and allow the elimination of the joint-fill compound from the joint.

SRM Nozzle-to-Case Joint: Potential Location for NASA Glenn Thermal Barrier



This chart shows where Thiokol plans to use the thermal barrier in the nozzle-to-case joint of the Shuttle solid rocket motor. The figure at the bottom is an enlarged area of the rocket nozzle showing the nozzle-to-case joint and nozzle joints one through five. Thiokol has recently begun an aggressive plan to qualify the thermal barrier for use in Joint 2 and is considering using it in other nozzle joints. The figure at the top is an enlarged view of the nozzle-to-case joint. The primary, secondary, and wiper O-rings are shown along with the phenolic insulation (in orange) and the surrounding metal hardware (in blue). The thermal barrier is highlighted in its position upstream of the O-rings where it would help block hot combustion gases from reaching the O-rings.

Thermal Barrier Has Unique Requirements



- **Sustain extreme temperatures (2500-5500°F) during Shuttle solid rocket motor burn (2 min. 4 sec.) without loss of integrity. Expected joint cavity fill time less than 10 sec.**
- **Drop gas temperatures in joint (3200°F) to levels acceptable to Viton O-rings and prevent O-ring char and erosion.**
- **Diffuse/spread narrow (.08 diameter) hot gas jet reducing the energy/unit area.**
- **Block hot slag entrained in gas stream from reaching O-rings.**
- **Exhibit adequate resiliency/springback to accommodate limited joint movement and manufacturing tolerances in these large nozzle segments (diam. 8.5').**
- **Endure storage for up to 5 years.**

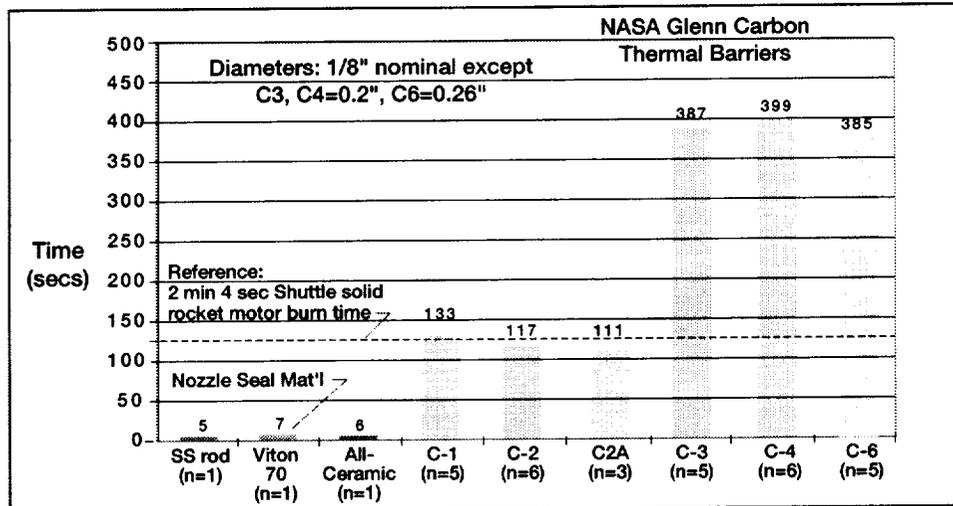
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To be used in the nozzle-to-case joint of the Shuttle solid rocket motors, the thermal barrier has several unique requirements. It must be able to withstand extreme temperatures of up to 5500°F during the Shuttle solid rocket motor burn time of 2 minutes 4 seconds without loss of integrity. Although the rocket burns for over two minutes, the thermal barrier actually only has to endure these extreme temperatures for less than ten seconds. As hot gases flow through the permeable thermal barrier, they fill the cavity between the thermal barrier and the downstream wiper O-ring. Once the pressure across the thermal barrier equilibrates, hot gases stop flowing into the cavity. Therefore, the thermal barrier must be able to drop the hot gas temperature in the joint to levels that the Viton O-rings can withstand to protect the O-rings from charring and erosion. The thermal barrier also has to be able to diffuse and spread narrow hot gas jets with diameters of 0.08 inches to prevent them from impinging on the O-rings. The thermal barrier has to filter hot slag out of the gas stream to prevent it from reaching the O-rings. It must exhibit adequate resiliency to accommodate limited joint movement and manufacturing tolerances in these large nozzle segments with diameters of 8.5 feet. Finally, the thermal barrier has to be able to endure storage for up to five years. Once the rockets are assembled, they often sit for several years before they are used.

Burn Time of Candidate Thermal Barrier Materials



Oxyacetylene Torch Results

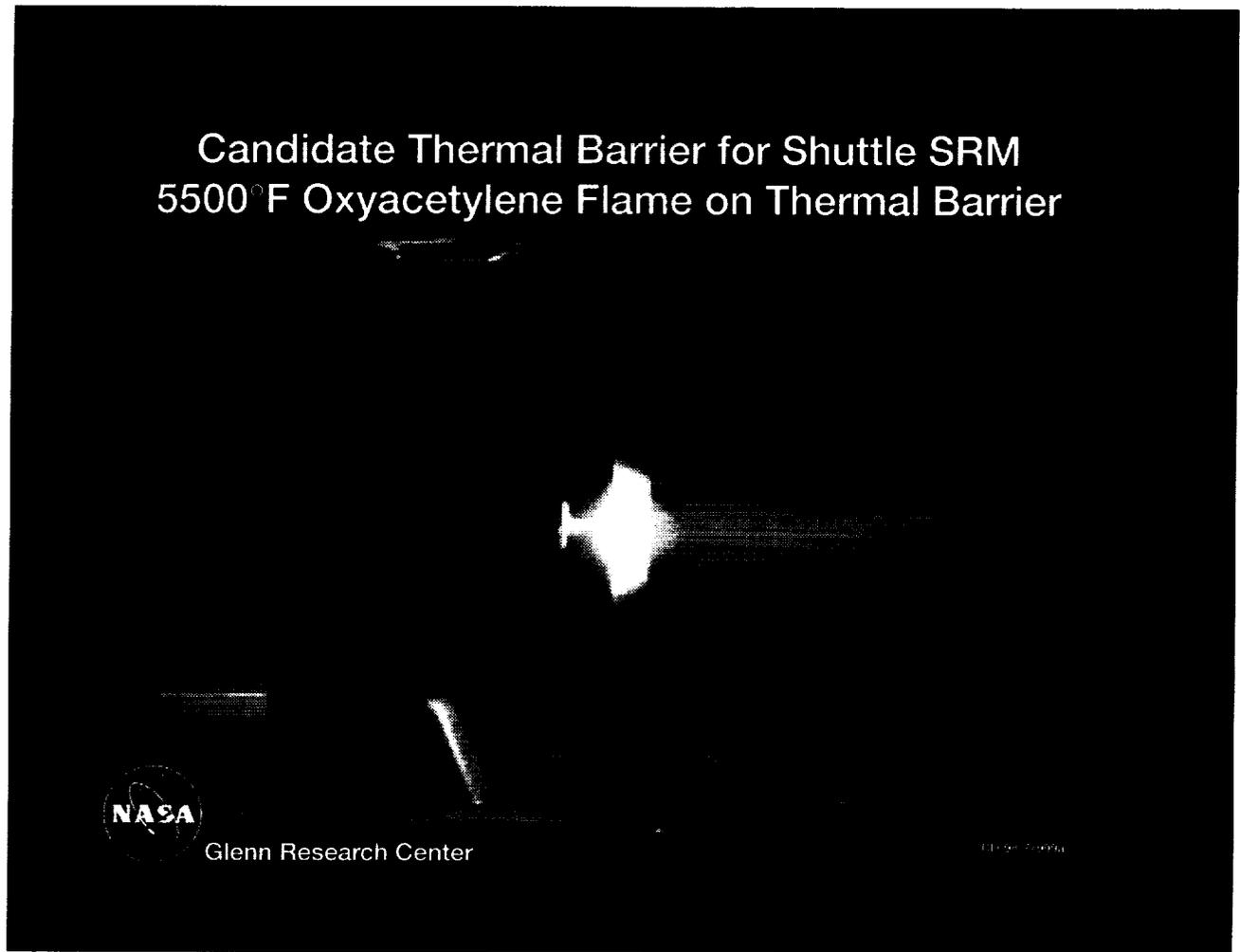


- NASA Glenn braided carbon thermal barrier (C-6) resists flame for over 6 minutes: Expected joint cavity fill time ≤ 10 sec
- Anticipated carbon barrier mass-loss mechanism: Carbon fiber oxidation
- Carbon sublimation temperature (6900°F) > Rocket hot gas temperature (5500°F)
- Test believed to be conservative for carbon thermal barriers as rocket exhaust chemistry is less oxidative than torch burn test

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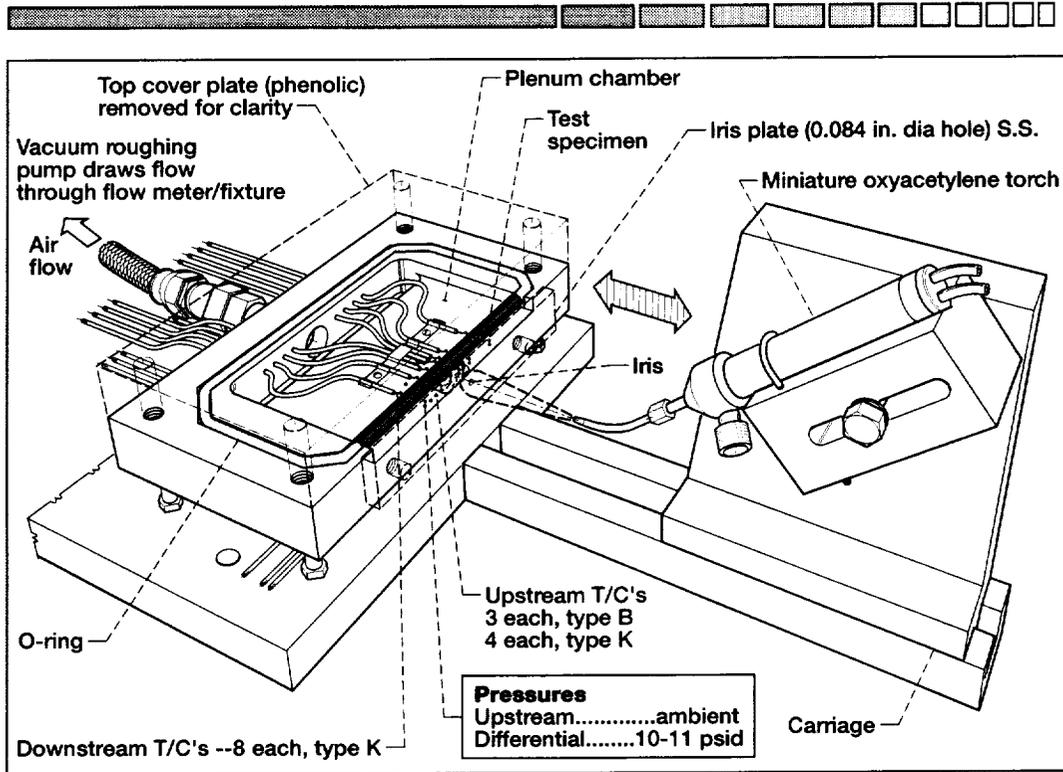
When Thiokol first approached NASA Glenn about this problem, we devised a simple test to screen different thermal barrier materials and designs. Candidate materials were subjected to a test in which specimens were placed into the flame of an oxyacetylene torch and the amount of time to completely burn through them was measured. The torch was adjusted until a neutral flame was formed, and the thermal barrier materials were placed in the hottest part of the flame at the tip of the inner cone where temperatures reached 5500°F. This chart shows the results of burn tests performed on candidate thermal barrier materials and designs. It shows the amount of time that it took for the oxyacetylene torch to cut completely through the different materials. All of the specimens were 1/8" in diameter except the Carbon-3 (C-3) and Carbon-4 (C-4) designs, which were 0.2" in diameter, and the Carbon-6 (C-6) design that was 0.26" in diameter. Thiokol is evaluating the C-6 design for the nozzle-to-case joint and for Joint 2. The first specimen that was tested was a 1/8" diameter stainless steel rod to get a reference point on how hot the flame was. This rod was cut through in only 5 seconds, and the metal was actually melted where the flame cut through. Next, a 1/8" diameter Viton O-ring, the same material used for the O-rings in the rocket nozzle, was tested. It was cut through in about 7 seconds. An all-ceramic seal design was tested next, and it only lasted 6 seconds in the flame. At this point, we realized that we needed to evaluate other material systems, so we designed arrangements braided out of carbon fibers. The three 1/8" diameter carbon fiber designs all lasted about 2 minutes in the oxyacetylene flame. As a point of comparison again, the Shuttle solid rocket motor burn time of 2 minutes 4 seconds is indicated in the figure. Moving up in diameter, the C-3 and C-4 designs with diameters of 0.2" and the C-6 design at 0.26" lasted about six and a half minutes in the flame. Thus, these thermal barriers can endure 5500°F gases for over three times longer than the solid rockets are actually in operation. After the carbon thermal barriers were removed from the flame, the areas where the flame cut through them were just as soft and flexible as before they were tested. There were no signs of melting, charring, or embrittlement. We believe that the carbon fibers were actually being oxidized as they were cut through. Carbon fibers oxidize at temperatures above 600 to 900°F depending on the type of fiber. At the other end of the spectrum, the sublimation temperature of carbon is 6900°F. Therefore, the temperature of the rocket and the oxyacetylene torch at 5500°F is hot enough for oxidation of the fibers but not hot enough for sublimation to occur. Also, these tests are probably conservative in terms of burn resistance because they were performed in an oxidizing ambient atmosphere. The rocket exhaust chemistry is not as oxidative, though. It is possible that the carbon thermal barriers could be exposed to rocket exhaust in the Shuttle solid rocket motors and not even be effected.

Candidate Thermal Barrier for Shuttle SRM 5500°F Oxyacetylene Flame on Thermal Barrier



This chart shows the thermal barrier while it is being exposed to the oxyacetylene torch. An incandescent fireball can be seen around the thermal barrier, which is positioned at the tip of the inner cone of the flame. In actuality, this fireball is too bright to look at with the naked eye, and welding glasses must be used to view the test. However, this image was taken with a digital camera that filtered out the brightness of the flame.

Temperature Drop Test Fixture



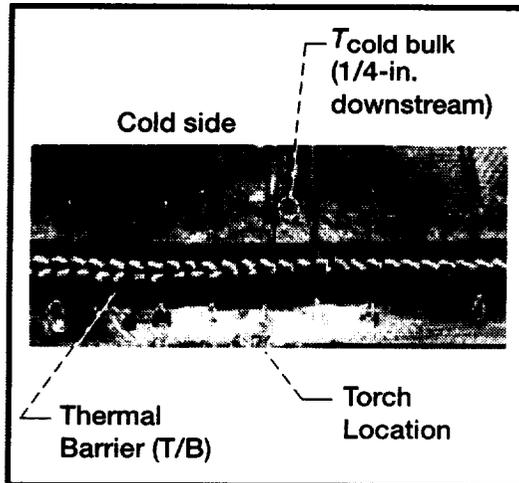
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Although the burn tests showed that the carbon thermal barrier designs could resist extreme temperatures for extended periods of time, a test method was required that would more accurately simulate the conditions that the thermal barrier would be subjected to in a rocket. Therefore, we designed a new fixture to measure the temperature drop across and along the thermal barrier in a compressed state when subjected to narrow jets of hot gas at upstream temperatures of 3000°F. The thermal barrier was compressed between two plates of phenolic material to simulate the insulation of the solid rocket motors. Specimens were instrumented with thermocouples on both their upstream and downstream sides to measure the temperature drop across and along the specimen when it was exposed to a hot gas jet from a miniature oxyacetylene torch. An "iris plate" was secured between the torch and the specimen, and a hole in this plate focussed the flame of the torch into a narrow 0.08-inch diameter jet. A vacuum roughing pump hooked up to the plenum chamber downstream of the specimen ensured that hot gas flow from the torch was drawn through the specimen. A flow meter downstream of the fixture measured the amount of flow that passed through the specimen during a test. Pressure transducers measured the upstream pressure (ambient) and differential pressure (10-11 psid) across the specimen. Tests were typically conducted for about a thirty-second torch application.

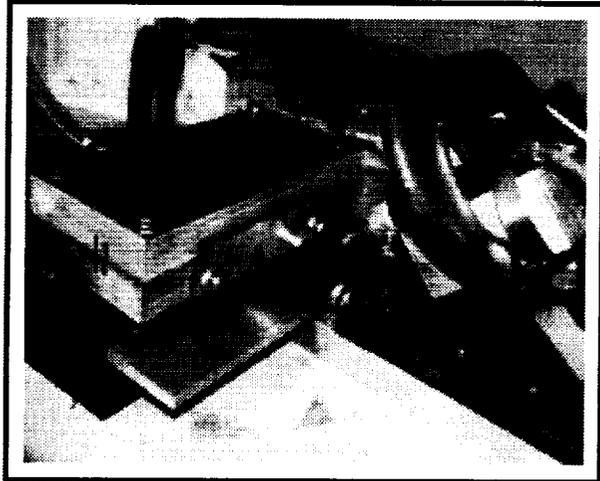
Temperature Drop Fixture Photographs



Close-Up Showing Thermal Barrier and Instrumentation



Test in Progress



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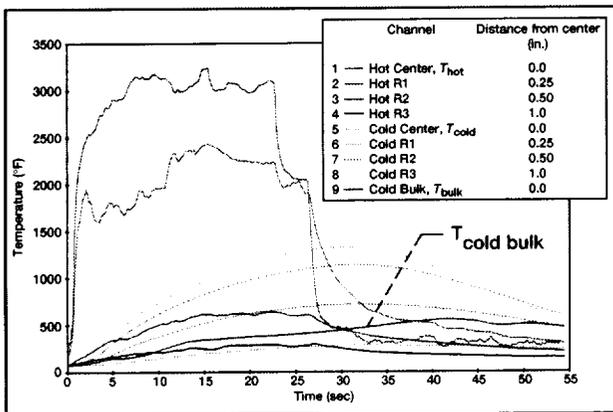
This chart shows two photographs of the temperature drop test fixture. The photo on the left shows a specimen as it is instrumented with thermocouples. A pair of thermocouples was aligned directly in the center of the hot gas jet on the upstream and downstream sides of the specimen. Additional thermocouples were placed 1/4", 1/2", and 1" away from the center thermocouples on both sides of the specimen. The tips of the thermocouples were tucked into the outermost sheath layer to measure the surface temperature of the specimen during a test. An additional thermocouple was located 1/4" downstream of the specimen in line with the center thermocouples to measure the temperature drop one specimen diameter downstream. This was referred to as the "cold bulk" temperature.

The photo on the right shows the fixture as the torch is being moved toward the iris plate.

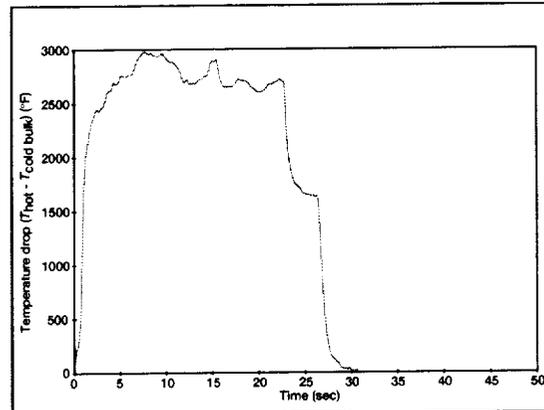
Temperature Drop Test Results: C-6



Temperature vs. Time
Hot/Cold Sides and $T_{\text{cold bulk}}$



Temperature Drop
($T_{\text{hot}} - T_{\text{cold bulk}}$) vs. Time



$T_{\text{cold bulk}}$ = Temperature 1/4-in. downstream, aligned with centerline of jet

Thermal barrier—C-6 (0.26" dia.; less dense braid):

- Sustains 2900-3000 °F for 20 sec (2x joint cavity fill time)
- Causes a large temperature drop of 2500-2900 °F ($T_{\text{hot}} - T_{\text{cold bulk}}$)

Temperature 1/4-in. downstream stays within Viton O-ring temperature limit

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This chart shows the results of temperature drop tests performed on the 0.26" diameter C-6 thermal barrier. The plot on the left shows temperature traces recorded for a 20 to 25 second torch exposure. Temperature traces for the center thermocouples and those to the right of center on both the upstream and downstream sides of the thermal barrier are shown in degrees Fahrenheit. Thermocouple readings to the left of center were symmetric to those to the right of center and are not shown here for clarity. One can see that the center thermocouple on the hot side reached about 3200°F and that the temperature readings decreased for the thermocouples farther from center. The center thermocouple on the cold side reached about 1200°F with temperatures dropping away from center. Even after a 20 to 25 second torch exposure, the temperature 1/4" downstream of the thermal barrier barely reached 500°F, well within the Viton O-ring temperature limit.

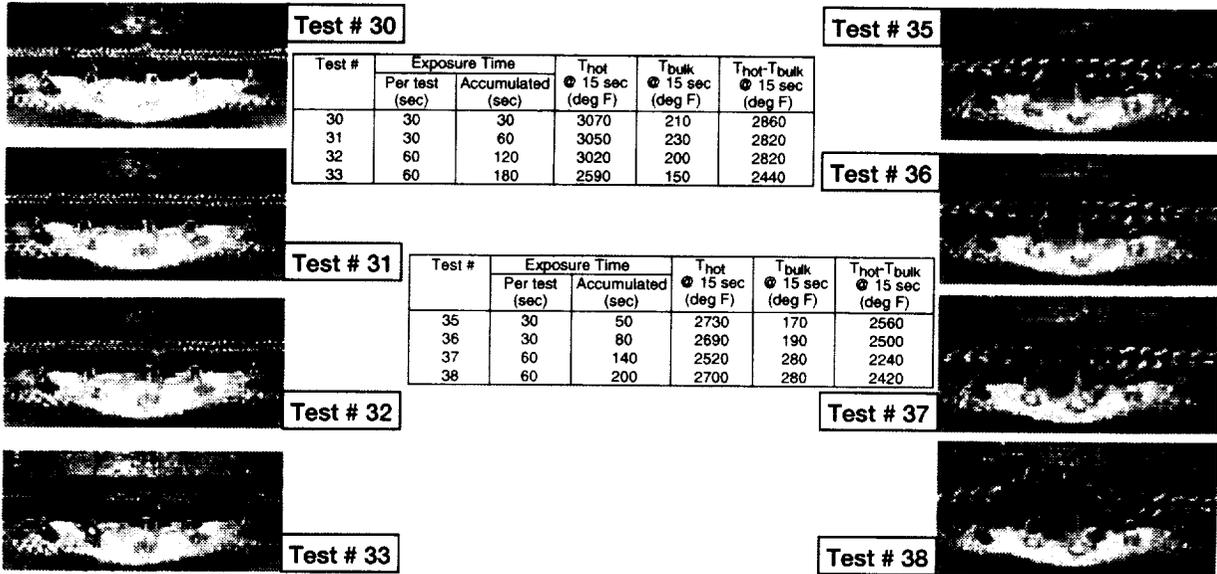
The plot on the right shows the temperature difference between the center thermocouple on the hot side and the cold bulk temperature. A large temperature drop of 2500 to 2900°F was observed during this test.

Thermal Barrier Condition vs. Accumulated Time



C-3 Thermal Barrier

C-6 Thermal barrier



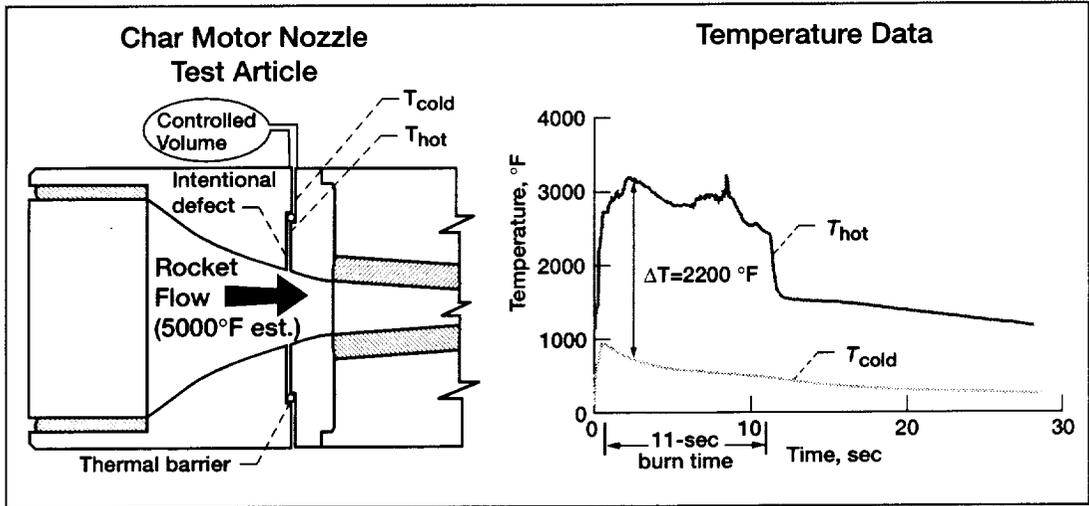
- C-3 and C-6 sustained 2500-3000 °F for 60 second intervals (180-200 sec accumulated time) with little damage. C-3: 0.029-in. recession; C-6: 0.092-in. recession.

No evidence of hot gas path around thermal barrier

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This chart shows the results of repeated torch exposures on one C-6 specimen. The four photos on the right side show the condition of the specimen after two torch exposures of 30 seconds and two exposures of 60 seconds for a total of over three minutes of torch exposure. There was some minor damage to the specimen by the end of the fourth test, but the majority of the cross section was still intact, and there were no signs of hot gas paths around the specimen. This series of tests was much longer and more extreme than what the thermal barrier would be exposed to in the solid rocket motor.

Thiokol Char Motor Test Results: C-6 Thermal Barrier



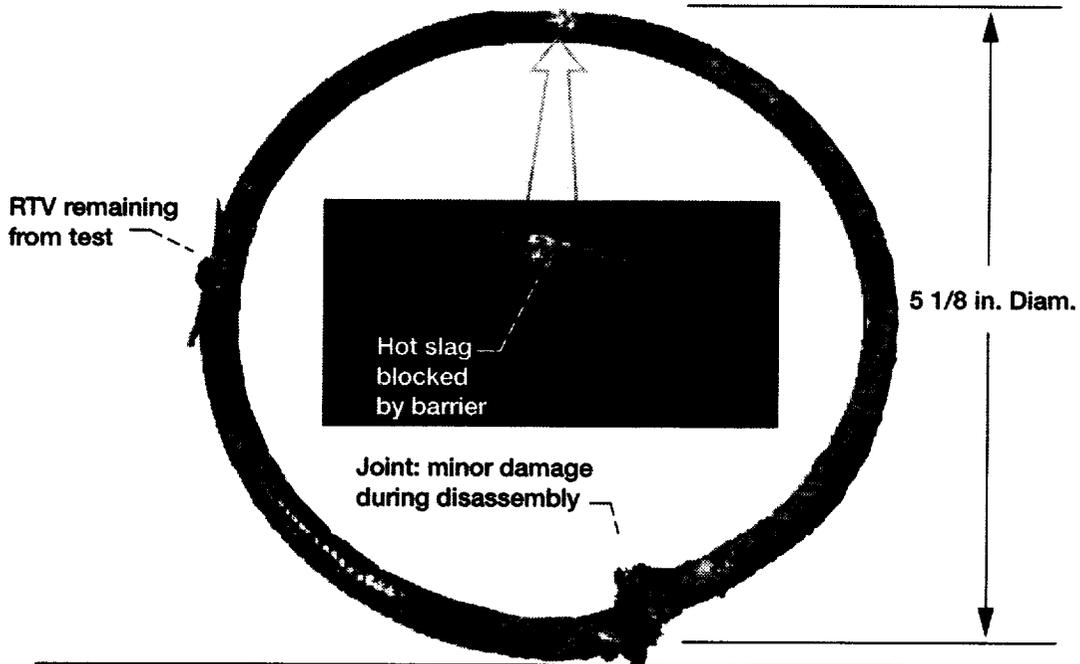
- Char motor test with intentional large joint defect (0.060") subjects thermal barrier to hot rocket gas for temperature and material performance evaluation
- Thermal barrier performed extremely well subjected to hot gas (3200 °F) for 11 sec firing – simulating maximum downstream cavity fill time
- Thermal barrier reduced incoming gas temperature 2200 °F, spread the incoming jet-flow, and blocked hot slag thereby offering protection to O-rings

Thermal barrier: C-6, 0.26" diameter

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Thiokol has performed a series of tests in a subscale rocket "char motor" in which the thermal barrier was exposed to hot rocket gases. The figure on the left shows the test setup in which hot gases passed through an intentional 0.06" wide joint defect and impinged on the thermal barrier before filling a controlled downstream volume. Pressures and temperatures were measured both upstream and downstream of the thermal barrier. The plot on the right shows temperature traces from a test performed on a 0.26" diameter C-6 thermal barrier specimen in the char motor. The thermal barrier performed extremely well while withstanding hot side temperatures of 3200°F for an eleven-second rocket firing. It dropped the temperature by 2200°F across its diameter, spread the incoming hot gas flow, and blocked hot slag. When the specimen was removed from the char motor, it was in excellent condition with no apparent burning or charring. These test results were consistent with the results from our temperature drop tests in which we measured 2500+°F drops across the same C-6 thermal barrier design.

Thiokol Char Motor Thermal Barrier (C-6) After Test



Char motor tests demonstrate thermal barrier effectiveness: blocks 3200 °F gas for 11 sec joint fill time, blocks hot slag, and shows minimal damage

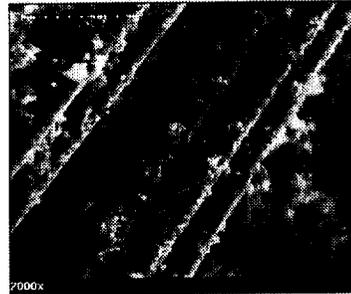
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This is a photograph of the specimen that Thiokol tested in the char motor in the previous chart. The specimen was in very good condition with only minor damage at the splice joint caused during disassembly. There were no signs of burning or charring of the specimen, but deposits could clearly be seen both on and between the carbon fibers.

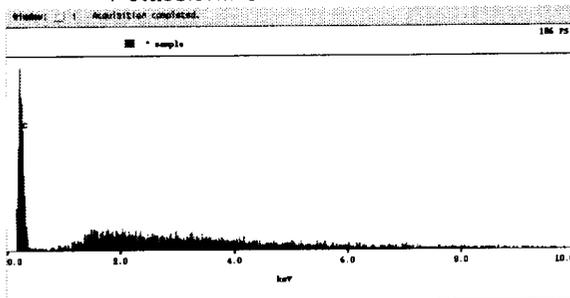
NASA GRC Examination of Thermal Barrier from Char Motor Test

■ Observations

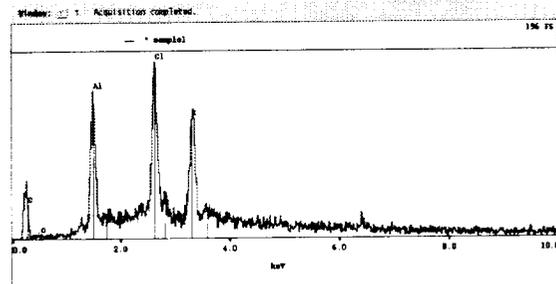
- Chemical analysis of as-received thermal barrier showed only carbon present
- Chemical analysis of char motor specimen revealed presence of: aluminum, silicon, chlorine, potassium, and carbon
- Potential sources: Aluminum: Rocket fuel;
Silicon: Chopped silica phenolic insulation blocks;
Chlorine: Ammonium perchlorate oxidizer;
Potassium: Unknown



SEM Photo of Upstream Side of Thermal Barrier (2000X)



Chemical Analysis of As-Received Thermal Barrier



Chemical Analysis of Thermal Barrier After Char Motor Test (2000X)

To further examine the thermal barrier specimen that was tested in the Thiokol char motor, we sectioned the specimen and examined it in a scanning electron microscope. The image at the upper right shows that there was no damage to individual carbon fibers within the specimen. The fibers were still cylindrical and relatively smooth. The thermal barrier did act as an effective slag barrier, though, filtering out particles and trapping them on and between the carbon fibers. To analyze the deposits even further, a chemical analysis was performed on them. At the bottom left of this chart is a chemical analysis of an as-received specimen that had not been tested in the char motor. As would be expected, the only peak that showed up was for carbon, since there were very few other deposits or impurities in the specimen. At the lower right is the plot of the chemical analysis performed on the specimen that was tested in the char motor. This test revealed the presence of aluminum, silicon, chlorine, and potassium in addition to carbon. Through discussions with Thiokol, the presence of all of these species was explained. The aluminum came from the solid fuel used in the rocket. The silicon most likely was deposited on the specimen as the chopped silica phenolic insulation blocks around the specimen became charred. The chlorine came from the ammonium perchlorate oxidizer, and the potassium came from the igniter used to fire the rocket.

NASA GRC Thermal Barrier Feasibility Proven in MNASA-10 RSRM



Successful firing of MNASA RSRM-10 motor

The successful firing of the MNASA RSRM-10 motor was a major milestone in the development of the MNASA RSRM-10 motor. The motor was fired for 29 seconds, demonstrating the feasibility of the thermal barrier design. The results of this test demonstrated that the thermal barrier is capable of protecting downstream O-rings from hot rocket gases in large-scale solid rocket motors.

■ Test Parameters

- Carbon-6 thermal barrier tested in MNASA-10 1/5th-scale version of full-scale reusable solid rocket motor (RSRM) used to launch space shuttle
- Specimen tested in redesigned nozzle-to-case joint with intentional flaw in nozzle insulation
- Rocket motor fired for 29 seconds

■ Observations

- Hot combustion gases reached thermal barrier: Soot observed upstream of thermal barrier
- No soot downstream
- No damage or erosion to thermal barrier or downstream O-rings

On August 10, 1999, the Carbon-6 thermal barrier was tested in an MNASA-10 1/5th-scale version of the full-scale solid rocket motors used to launch the Space Shuttle. Tested in a redesigned nozzle-to-case joint for a 29 second rocket firing, an intentional flaw in the nozzle insulation allowed hot combustion gases to reach the thermal barrier as evidenced by soot observed on hardware upstream of the thermal barrier. Post-test inspection revealed no soot downstream of the thermal barrier and no damage or erosion to either the thermal barrier or to downstream O-rings that the thermal barrier is designed to protect. The results of this test demonstrated that the thermal barrier is capable of protecting downstream O-rings from hot rocket gases in large-scale solid rocket motors.

Summary and Conclusions



NASA Glenn thermal barriers resist 5500°F flame for greater than 6 minutes before burn-through:

- Expected joint cavity fill time ≤ 10 sec.
- Anticipated mass-loss mechanism: Carbon oxidation

Braided thermal barriers:

- Permit gas flow to fill joint cavity and cause a large (2200 °F and above) temperature drop through diameter
- Spread flame preventing pass-through of damaging focused jet
- Protect downstream Viton O-ring: gas temperatures 1/4-in. downstream of barrier are within Viton O-ring temperature limit
- Exhibit adequate resilience to accommodate joint movement

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In summary, the NASA Glenn thermal barrier has demonstrated the ability to resist the 5500°F flame of an oxy-acetylene torch for over six minutes before being cut through. This is much longer than the expected nozzle-to-case joint cavity fill time of less than ten seconds that it would have to endure in the solid rocket motors. It is believed that the actual mass-loss mechanism involved in this process is oxidation of the carbon fibers that make up the thermal barrier. The thermal barrier is permeable enough to permit gas to flow through it to fill the downstream joint cavity while at the same time causing a large (2200+°F) temperature drop across its diameter. It protects downstream Viton O-rings by spreading focussed hot gas jets and lowering gas temperatures to within the Viton temperature limit. The thermal barrier also exhibits adequate resiliency to accommodate joint movements.

Summary and Conclusions (Concluded)



Thiokol Char Motor Results

- **Thermal barrier performed extremely well subjected to hot gas (3200 °F) for 11 sec firing—simulating maximum downstream joint cavity fill time**
- **Thermal barrier reduced incoming gas temperature 2200 °F, spread incoming jet-flow, and blocked hot slag thereby offering protection to O-rings.**

Thermal barrier feasibility established qualifying it for comprehensive evaluation

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Results of char motor tests that Thiokol conducted showed that the thermal barrier performed extremely well when subjected to 3200°F hot gases for an eleven second rocket firing. It reduced the incoming hot gas temperature by 2200°F, spread incoming gas jets, and blocked hot slag to protect the downstream O-rings. Results of the most recent MNASA rocket tests on the thermal barrier showed that it blocked soot with no damage to either the thermal barrier or the downstream O-rings. All of these positive results have qualified the thermal barrier for further testing and evaluation to qualify it for use in the nozzle-to-case joint and Joint 2 of the Shuttle solid rocket motors.

Planned Future Work



- **NASA Glenn:** Evaluate performance characteristics of future generation thermal barriers
- **Thiokol:** Further evaluate thermal barrier performance in char motor and other joint simulation tests.
- **Thiokol/NASA Marshall:** Perform full-scale solid rocket motor tests with NASA Glenn designed thermal barriers

Schedule

- | | |
|-------------------------------|------------|
| - Redesigned joint, Nominal | Jan, 2001 |
| - Redesigned joint, with flaw | May, 2002 |
| - First shuttle flight | Sept, 2002 |

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Thiokol's current test plan will culminate with testing of the thermal barrier in full-scale solid rocket motor tests of the redesigned joint in January 2001 (nominal condition, without flaw) and in May 2002 (with flaw). This all leads up to an anticipated first Shuttle flight using the thermal barrier in September 2002.

Seal Descriptors

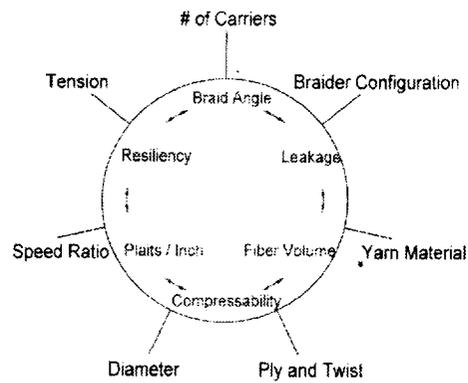
- Diameter
- Materials of construction
- Compressibility
- Resiliency
- Fiber volume
- Leakage

Albany International Techniweave



A finished seal can be described the these characteristics.

Braid Variables



Albany International Techniweave



The braiding parameters shown in blue can be changed independently of each other and will effect all of the characteristics shown in red. It is impossible to change any of the seal characteristics shown in red without effecting all of them. Thus the fabrication of a textile braid differs greatly from other manufacturing processes. The braid is a study in equilibriums, where all of the properties are interactive and cannot be held constant while changing only one variable.